Extended Abstracts of the 1999 International Conference on Solid State Devices and Materials, Tokyo, 1999, pp. 144–145 **A-7-1**

Invited

High-quality Epitaxial Growth of SiC and State-of-the-art Device Development

Hiroyuki Matsunami and Tsunenobu Kimoto

Department of Electronic Science and Engineering, Kyoto University
Yoshidahonmachi, Sakyo, Kyoto 606-8501, Japan
phone: +81-75-753-5340 Fax: +81-75-753-5342 e-mail:matsunam@kuee.kyoto-u.ac.jp

1. Introduction

Silicon Carbide (SiC) is a wide-gap semiconductor with many superior characteristics (high breakdown field strength, high saturation drift velocity, and high thermal conductivity). This material has been expected as a candidate for electronic devices in the next generation, such as high-power, low-loss, high-frequency/high-power, and high-temperature operating devices.

Nowadays, 6H- and 4H-SiC (typical polytypes) wafers of n- and p-types with a diameter of 50mm using a sublimation technique [1] are commercially available. In the middle 1980s, the author's group developed a new technique for growing a high-quality and polytype-controlled epitaxial layer of 6H- and 4H-SiC using step-flow growth. This method - step controlled epitaxy [2] - has become a technological breakthrough for quick advances in various electronic devices.

In this paper, homoepitaxial growth of SiC with high-quality is described together with characterization, and state-of-the-art SiC electronic devices are reviewed.

2. Epitaxial growth of SiC (Step-controlled epitaxy) and electrical characterization [3]

Epitaxial growth of 6H- and 4H-SiC has been carried out at around 1500℃ by atmospheric-pressure CVD using a substrate with an off-angle of several degrees along <11-20> on the {0001} plane of wafers. The source gases are SiH_4 and C_3H_8 with H_2 carrier gas. By utilizing step-flow growth at steps introduced by off-angle, single crystal growth of polytype identical to the substrate has been achieved.

By changing the C/Si ratio during CVD, a high-purity undoped epitaxial layer with a donor concentration of $5\times10^{13}cm^{-3}$ can be obtained. By in-situ doping with either N_2 gas or TMA, a doping level of $10^{19}cm^{-3}$ is available for both n- and p-type epitaxial layers. An electron mobility of $850cm^2/Vs$ was obtained for 4H-SiC at room temperature. The mobility of 4H-SiC is about twice as that of 6H-SiC. There is no reduction of mobility due to ionized scattering centers at a low temperature down to 77K. The measured electric breakdown field strength is in $2\text{-}5\times10^6V/cm$ (donor concentrations of $3\times10^{15}\text{-}3\times10^{18}cm^{-3}$).

3. State-of-the-art SiC devices [4]

High-frequency devices

MESFETs were fabricated using n-type epilayers on V-doped 4H-SiC (insulating substrate) with 0.6 μm gate, and a f_{max} of 42GHz with a power density of 3.3W/mm at 10GHz was reported (a total power of 6.2W for 1.92mm periphery). Recently, a 4H-SiC MESFET with a total power of 80W (CW, 3.1GHz) in a chip (1x4mm) was announced.

SITs of n-type 4H-SiC were demonstrated using Schottky gates for finger structure fabricated by RIE, whose f_{max} of 4GHz is limited by the finger space. A total power of 450W (pulse mode) was realized at 600MHz using 23 SITs in a power-transistor package of 0.4inch. A transmitter for a HDTV system with a peak power of 2.5kW was realized.

High-power devices

High-voltage (1.75kV) Schottky diodes with a low onresistance (R_{on}) of 5mΩcm^2 were announced with Ti/4H-SiC (13μm) using implanted B as an edge termination. Then, a breakdown voltage (V_b) of 3kV was obtained using a 42μm thick epitaxial layer. Schottky diodes of 1-1.4mm^2 in a package were used in a 1.4kV power electronics circuit of Si IGBT, indicating a tremendous reduction of switching loss compared with Si p-i-n diodes.

Today's highest value of blocking voltage is 5.9kV using 4H-SiC p-n junction (epilayer thickness:50μm) mesa structure guarded with JTE (Junction Termination Extension). Ion-implantation has been utilized to fabricate p-n junction diodes.

Power UMOSFETs (trench U-shape) were demonstrated with 4H-SiC with a V_b of 260V and an R_{on} of 18mΩcm^2 (channel mobility: 11cm^2/Vs). Then, they were developed to a V_b of 1.4kV and R_{on} of 311mΩcm^2. The value of R_{on} just passed the limit of Si MOSFET.

DI(double-implanted)MOSFETs using 6H-SiC were proposed with a V_b of 760V and R_{on} of 125mΩcm^2, and their characteristics were improved to a V_b of 1.85kV and R_{on} of 46mΩcm^2 which is 30 times better than the Si theoretical limit.

To improve the low inversion-channel mobility in SiC MOSFETs, epi-channel FETs (EC-FETs) were proposed. Hexagonal shape 4H-SiC MOSFET cells were fabricated in a 2x2mm chip with a V_b of 450V and R_{on} of 10.9mΩcm^2 (channel mobility:108cm^2/Vs). The idea was developed to 4H-SiC accumulation-channel FETs (ACCUFETs) with a V_b of 1.4kV and R_{on} of 15.7mΩcm^2).

P-n-p-n(substrate) thyristors with a V_b of 900V and R_{on} of 1.7mΩcm^2 and GTO with a V_b of 1kV have been demonstrated. P-channel IGBTs have also been demonstrated with a V_b of 800V.

High-temperature operating devices

As a recent progress in high-temperature operating integrated circuit devices, 6H-SiC CMOSIC which can operate at 5V, and a ring oscillator of 11 steps operated with 24.8kHz at 300℃ have been demonstrated.

4. Summary

Step-controlled epitaxy to get high-quality SiC epitaxial layers was described together with the epilayer characteristics. State-of-the-art SiC device development was reviewed. By improving substrate quality and processes for device fabrication, SiC devices will take the position in near future.

Acknowledgement

This work has been supported by a Grant-in-Aid for Specially Promoted Research from the Ministry of Education, Science, Sports, and Culture of Japan.

References

1. Y.M.Tairov and V.F.Tsvetkov, J. Cryst. Growth **52**, 146 (1981).

2. N.Kuroda, K.Shibahara, W.S.Yoo, S.Nishino, and H.Matsunami, Ext. Abstr. the 19th Conf. on Solid State Devices and Materials (1987, Tokyo) (1987) p227.

3. for example, H.Matsunami and T.Kimoto, Materials Science and Engineering **R20**, 125 (1997), and its references.

4. for example, Silicon Carbide, Ⅲ-Nitrides and Related Materials, Part 2 (Trans Tech Publication, Switzerland, 1998).